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RESEARCH REQUIREMENTS FOR THE REDUCTION OF HELICOPTER VIBRATION

By

Glidden S. Doman

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By
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FOREWORD

This report was prepared by the Boeing Vertol Company for the National Aeronautics and Space Administration, Langley Research Center, under NASA Contract NAS1-13624. William Snyder was NASA Program Manager for these studies. The Boeing Project Manager was Wayne Wiesner.

SUMMARY

A study was conducted in which all prospective approaches to the reduction of helicopter vibrations were searched to establish insight for the planning of a corrective research program. To assure that all approaches would be considered, abstracts of 211 potentially relevant project reports and technical studies were retrieved. Of these, 24 documents were found to be significant and are listed as references.

The state of the art as revealed in the literature is summed up and followed by a discussion of state-of-the-art solutions and of identified technological gaps. Nine research tasks intended to fill these gaps are prioritized and discussed in terms of the current status of related technology. The needed research can be seen to progress from basic to applied. It is applicable to all helicopters without regard to size.

It is concluded that extending the historic trend toward lower vibration levels will require the successful application of principles which isolate the fuselage from the rotor systems. Simplicity of the necessary isolation systems should be facilitated by providing other refinements of the dynamic design of the system.

There is little cause to doubt that an excellent result can be achieved. The needed research should provide knowledge for its accomplishment in a manner which is simple, cost-effective, and without significant negative design interactions.

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1.0 INTRODUCTION

The helicopter industry has confirmed a vibration tendency in rotary-wing aircraft during 35 years of development effort and broadening operational experience. Improvement has been substantial and standards of acceptability have risen in step with corrective progress, but it remains unusual for a helicopter to be credited with good vibration characteristics.

Study of the causes of the problem and of the corrective means so far applied reveals that progress to date has mostly come from dynamic refinements rather than from changes in the design approach to the problem. It also becomes apparent that new approaches will be needed if the vibration rating of the helicopter is to progress from the present "much better" status to a rating of "good" or "excellent".

There is a current proliferation of research projects which have vibration control as their aim. This appears to reflect an industry judgment that the present "much better" rating is not satisfactory. The study reported herein examines the total situation and defines a recommended research program which should provide the technology to industry by 1985 to reduce all vibration levels to less than ±0.05g. In more familiar terms, the goal is to attain vibration levels approaching those in a jet airplane.

The ill effects of contemporary helicopter vibration levels upon reliability and maintenance experience are widely acknowledged and have been quantified to some degree in controlled operational testing such as that reported in reference 1. These effects have first-order influence upon operating costs. Prospective weight savings in a design which provides continuously low vibration levels can also increase helicopter productivity. More difficult to quantify but probably equally critical to commercial success is the passenger comfort and confidence that would be instilled by vibration-free flight. Useful insight can be gained, however, from studies of the human aspects such as in references 2, 3, 4, and 5. When the current situation is viewed in its entirety, the value of improving the design technology of vibration control becomes very clear.

The present study takes the need for improvement as a premise and explores the following questions:

1. What are the means available to reduce rotor-induced vibration?
2. What combination of these means will have least or no adverse impact upon the other aspects of cost?
3. What are the unknowns which must be probed in a research effort?
4. How should that research be conducted to emphasize high-payoff technologies?
5. What is the impact of design interactions and what levels of overall gain can be anticipated?

2.0 BASICS OF THE PROBLEM

The forward-flight operating environment of a helicopter blade creates vibratory airloads containing all harmonics of the rotor rotational frequency. These harmonics of the airloading are summed within the rotor. If we assume that all blades are identical, some cancel, others add and are transposed to the fixed-system coordinates of the fuselage. These are felt as vibratory forces and moments whose frequencies are integer multiples of the blade-passage frequency (number of blades times rotational frequency).

Those vibratory airloads that do pass through to the rotor shaft will have been modified by the response dynamics of the blades. Depending upon the presence of isolation features in the retention of the rotor shaft, some of these shaft loads may or may not reach the fuselage; instead they may be confined to the rotor and transmission systems. Of the vibratory loads that do pass into the fuselage, there mav be large variations in effect depending upon response dynamics of the fuselage structure.

Any design technology which solves the problem must achieve some combination of the following:

1. Reduction of the vibratory airloads.
2. Reduction of the dynamic response of the system to the vibratory airloads.
3. Absorption of vibratory loads at some point or points in the system.
4. Isolation of the fuselage or payload from vibratory loads and motions present in the rotor system.

It is useful to view the known, available approaches to vibration control in a chart such as Figure 2-1.

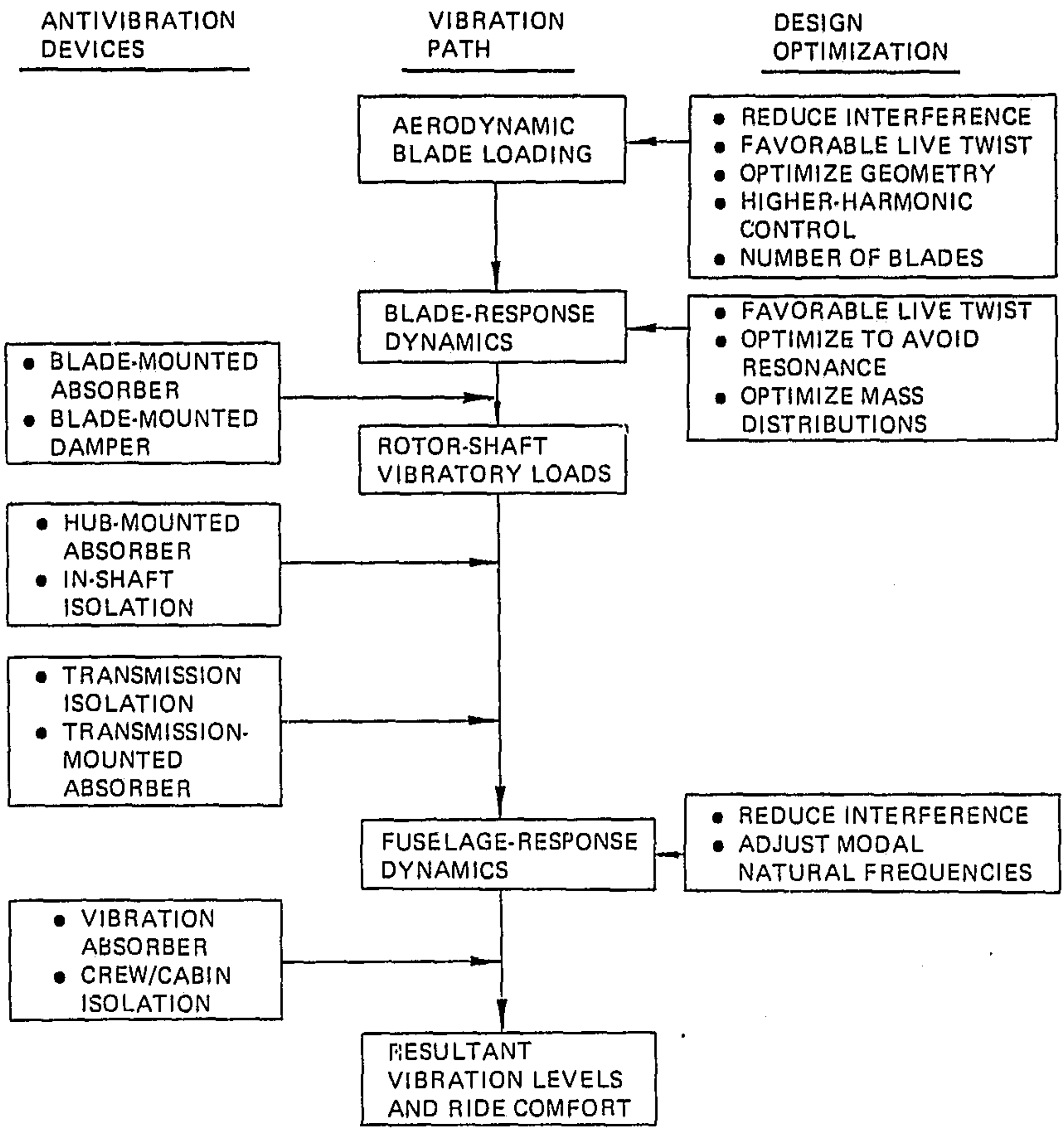

Figure 2–1. The known approaches to vibration control

3.0 STATE-OF-THE-ART SOLUTIONS

Because the vibratory airloads felt by the blade are transmitted to the helicopter as shear and bending moments at the blade root, the response dynamics of the blade can attenuate or amplify the loads felt at the hub. Thus, as a first and essential approach, the blade dynamic design tuning is commonly adjusted to reduce vibratory loads transmitted to the fuselage. A rigorous application of this refinement must consider the effects of coupling to the fuselage upon the dynamics of the blade. While not often applied with that degree of finesse, existing analytical technology is reasonably adequate for the purpose.

Fuselage dynamic response can then be tailored by adjusting fuselage modal natural frequencies so that they avoid resonance with those vibrations that do come through the shaft or come from vibratory aerodynamic pressures on the fuselage itself. Here again, existing analytical and experimental technology is reasonably adequate for the adjustment of modal natural frequencies. It is less reliable for quantitative prediction of mode shapes. Prediction of the aerodynamic loads which force the structure is the least-developed aspect of this technology.

A third approach in common use is the application of dynamic-absorption devices. Tuned centrifugal pendulum absorbers in the rotor system can arrest selected vibratory loads before they reach the rotor shaft. Fixed-tuned or self-tuning absorbers may also be placed on the fuselage structure to enforce local fixity on a selective basis. Theory and design practice for these devices are relatively mature, but the prediction of their weight and cost is difficult because the loads which they must accommodate are usually unknown at the design stage. Especially unreliable is the prediction of fuselage mode shapes as required to predetermine the best use of fuselage-mounted absorbers.

A fourth approach is the isolation of the fuselage or payload from the dynamic system. This involves some degree of uncoupling from the rotor blades so that selected vibratory loads will not be transmitted to the fixed system. The effect is always present to a significant degree in the hinges of articulated or teetering rotor systems. It frequently takes the form of a soft mounting of the transmission. A classic example is the soft mounting of the mast of two-bladed teetering systems to isolate their large in-plane aerodynamic vibratory loads. Main-rotor articulation configuration has had a major impact upon the choice of isolation versus absorption.

All successful contemporary helicopters employ design refinement to minimize blade and fuselage dynamic response. The residual problem is then attacked by providing some combination of rotor isolation and dynamic absorption. Means for reducing the vibratory airloads have not often been successfully applied except for avoidance of rotor-to-rotor and rotor-to-fuselage interferences.

A tradeoff between residual vibration level and growing system complexity has typified contemporary helicopter designs. A prime example has been the tendency to reject full and effective isolation of the rotors. This has occurred because, in a simple, passive isolation

system, excessive static deflections are encountered. Designers have declined to trade the added complexity of statically stiff but dynamically soft isolation devices for the further reduction of vibration levels. This reluctance to commit to full and effective isolation has been increased by a lack of analytical programs which consider rotor loads and stability as affected by fuselage impedance as felt through the isolator. The technology of isolation-system design is progressing rapidly and is beginning to support current design efforts to bring their approach to a mature state of the art.

4.0 CURRENT CONTRIBUTORY RESEARCH

Reduction or modification of the vibratory airloads encountered by the blade is the subject of two promising approaches to the vibration problem. Neither is yet state-of-the-art in the sense that its design application has been clearly evolved or explored. Both are subjects of current research effort.

4.1 Aeroelastically Adaptive Rotor Blades

Current research projects aimed at increasing normal helicopter advance ratios have shown that periodic blade torsion can be introduced to cause large reductions of blade-bending loads. Reference 6 presents an analytical approach, while reference 7 reports on wind-tunnel demonstration of bending-load suppression. The accompanying reduction of the moments and shears transmitted to the hub has the potential of reducing the magnitude or changing the character of the shaft vibratory loads that must be dealt with.

It can be reasoned that among the changes of blade dynamic-design features which are being explored for the other goals of aeroelastically adaptive rotor research, there will be opportunities to reduce or null one or more of the loads which would otherwise need isolation. Thus these new techniques of aeroelastic blade design should be examined for their potential in simplifying isolation systems or other elements of the antivibration design treatment.

4.2 Higher-Harmonic Control

Higher-harmonic control of the blade may be input in a manner which generates favorable changes of the vibratory forces or moments felt in the rotor shaft. The sensitivity of various rotor systems to this approach has been examined analytically in references 8 and 9. It has also been explored in wind-tunnel tests and in full-scale flight as reported in references 10, 11, and 12. Observed side effects upon performance, blade loads, and rotor operating limits are many and complex. The combination of sensors and actuating mechanisms needed in a prospective application is yet to be visualized. Interest in this approach is enhanced by its powerful and potentially broad capability.

Continuing investigations should reveal the essential side effects, define the elements needed in a viable system, and position the designer to evaluate the complexity/reliability/cost-effectiveness potential of such a system. Results will no doubt differ substantially for the various combinations of rotor-system articulation and isolation.

4.3 Airload Modeling and Control

Existing computer analytical programs handle blade-response dynamics with good engineering accuracy. With state-of-the-art extensions they can handle the response dynamics of the blade coupled to the fuselage with similar accuracy.

It is the modeling of the vibratory airloads encountered by the blade which is not adequate for vibration predictive purposes in present-day analytical programs. Peak-to-peak blade-bending responses are calculated with accuracy adequate for blade structural design. Phase and harmonic content are too inaccurate to permit calculation of the residual loads in the shaft after the blade-to-blade summation of root loads.

If effectively complete isolation of the rotor were achieved, there would be less need for a detailed knowledge of vibratory airloads. The residual vibratories would be confined to the rotor and transmission package where they would have little effect upon design features or weight. On the other hand, the design of an effective isolation system which is not unnecessarily complex demands a knowledge of the modes of motion of the rotor and transmission package when uncoupled. This in turn demands a knowledge of the character of the forcing airloads. Thus there is a clear need to gain a much-improved knowledge of the vibratory airloads.

Even with continued effort to improve the mathematical modeling of the sources of vibratory airloads, there will be an urgent need for data from suitably conducted wind-tunnel and flight tests. Analytical program validation and design of isolation systems will both benefit from the securing of now nonexistent airloads data.

Extensive research effort is being directed to easing of vibratory-loads sources which involve interblade encounters with tip vortices. Reduction of vortex intensity as sought in the work of reference 13 may contribute to an overall solution, as may the avoidance of vortex strikes as in the current variable-rotor-geometry investigation of reference 14.

Aerodynamic interference with the fuselage or other fixed surfaces in the rotor wake is another subject of numerous current investigations. It is important both as a source of vibratory blade and shaft loads, and as it creates vibratory pressures on fixed-system elements. The vibration-control aspect should be given more attention in current and contemplated configuration aerodynamics research.

5.0 SELECTION OF RESEARCH CONFIGURATION

5.1 Trends in Past Results Point to Isolation

When the vibration levels achieved and specified in procurement documents are plotted against the past 30 years of development effort, a steady improvement is revealed. Contributing to this trend was the advent of vibration-absorption devices which came into common use after 1967. Responsible in part for extending the trend of vibration-level improvement, these devices have tended to cost an increasing percentage of the design gross weight.

Figure 5-1 plots these trends and reveals that without isolation (except for in-plane force isolation in two-bladed systems) and without absorbers, vibration levels bottomed out at about ±0.2g. Absorbers brought this down to about ±0.1g at the expense of absorber weights which rose to 3 percent of gross.

Results of recent development of isolation systems have brought further drastic reductions of vibration levels and at reduced weight penalties. Plotted in Figure 5-2 for comparison with the trend lines, these results suggest that isolation is both superior in result and lower in weight penalty than the previous approaches have proved to be.

The significance of these trends as indicators that isolation will be a central feature of an advanced system is supported by the physics of the matter. Isolation in its simplest form uncouples the dynamic system and confines the vibratory loads to the existing masses and rotor-blade springs. Thus it does not require the addition of mass to absorb the forces.

5.2 The Essentials of Rotor Isolation

In the following discussion, the term "isolation system" will refer to mechanisms which are designed to uncouple the helicopter transmission, and therefore the rotor dynamic system, from the fuselage. This uncoupling will be as complete as possible for the pertinent vibratory loads, but must be made suitably stiff (coupled) for static loads. If the isolator simply consisted of very soft springs, rotor lift and drive torque would create intolerable static deflections. Similarly, the static moments commonly induced in the rotor shaft to provide for aircraft trim and maneuvering would create excessive angular deflections.

A large amount of design study and system development effort has been invested in search of compromise arrangements and corrective devices (ref. 15 through 20). The total impact of this prior work is that all the fundamental features of isolation systems have been explored and that the essentials of an excellent system can be readily quantified.

Not surprising is the fact that the simplicity of a candidate system is enhanced if one or more of its duties can be eliminated. For example, in teetering rotor systems where control and trim moments are not input to the rotor shaft, the isolator is relieved of any need to handle vibratory shaft moments because these too are precluded by the teetering freedom of the hub.

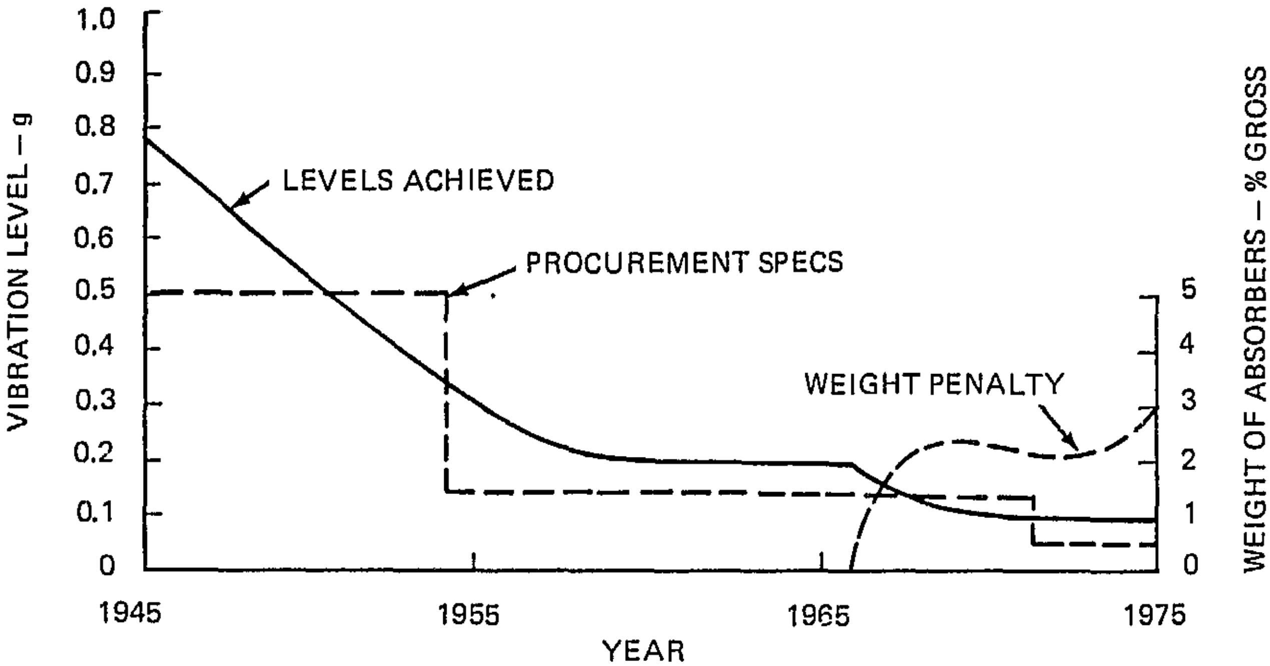

Figure 5–1. Trends of vibration control without isolation devices

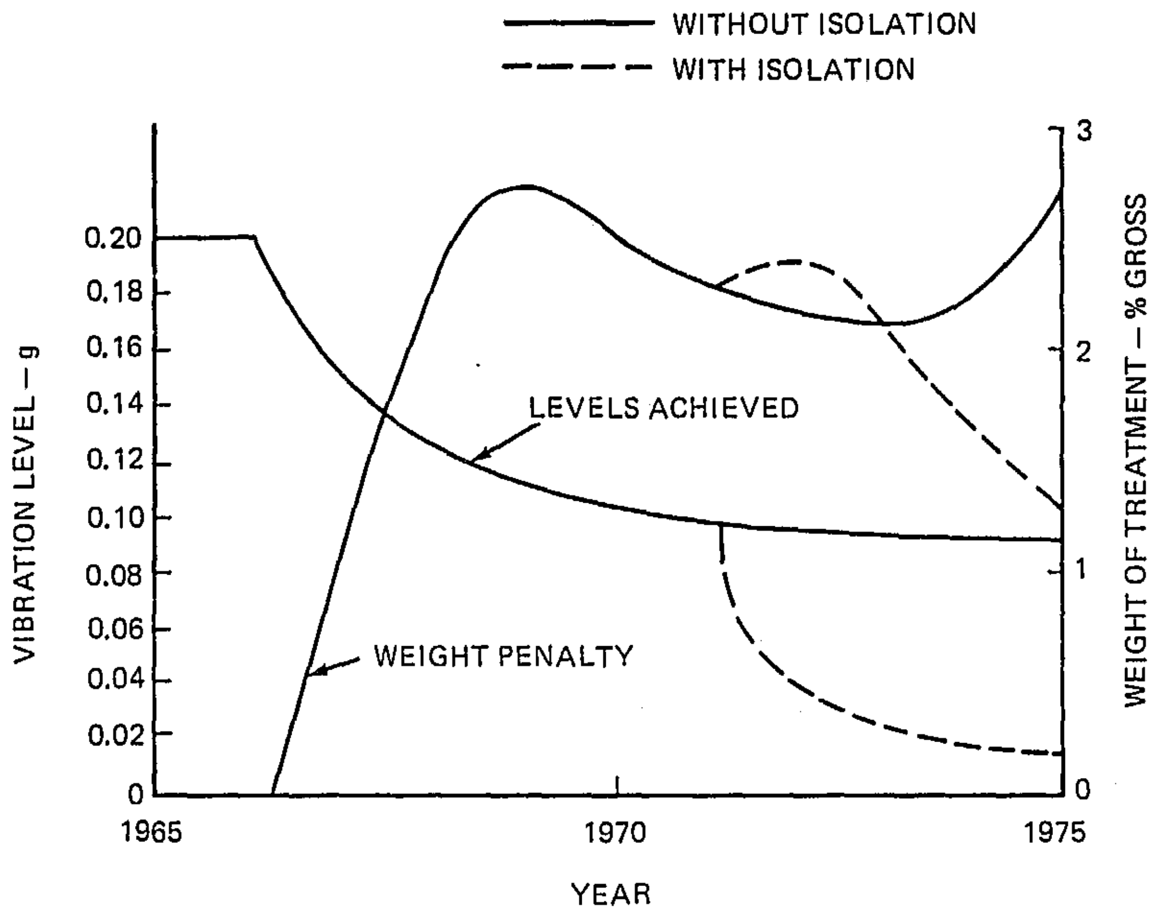

Figure 5–2. Trends of vibration control as affected by isolation devices

Thus (neglecting vibratory drive torques), the transmission can be disturbed only by horizontal and vertical forces passing through the teeter hinge. The dynamic uncoupling to isolate these forces can be provided by a soft, focalized mounting of the transmission so that it, the mast, and the hub can pitch and roll in response to horizontal rotor forces. The static deflections in pitch and roll are negligible because the teetering rotor does not generate steady shaft moments. Vertical vibratory forces are handled by other means independent of the above-described arrangement.

The simplicity of the system described is lost if shaft moment is introduced for control and trim purposes, such as maneuvering in zero-g flight. The control moments must be generated by springs around the teeter hinge and must be delivered to the fuselage through the isolator springs. Consequently, the isolator spring must become statically stiff while remaining dynamically soft. This in turn complicates the isolation system.

Loss of isolator simplicity also becomes inevitable when shaft moment control capability is introduced by the offset of flapping hinges or by the use of a hingeless rotor system. Passive isolation systems for pitch and roll vibratory moments must then handle relatively large control and trim moments as well. The isolator spring rates necessary for transmittal of the control loads are found to be so great that the transmissibility of the vibratory moments also becomes excessive. Effective isolation will typically be as poor as 20 percent.

Because the vibratory shaft-bending moments that must be isolated are typically largest in a hingeless system, the need and value of isolation is also greater than with an offset-hinged system. This apparent problem is eased somewhat by the fact that the stability of a hingeless rotor/isolator package is a simpler, more straightforward matter than that involving an articulated system.

The essentials of vibratory shaft-bending-moment isolation can be satisfied most simply by focalized transmission-mounting structures which do not provide isolation of vertical vibratory forces. Even greater simplicity is possible if isolation of vibratory drive torques is also omitted. Achievement of isolator simplicity therefore depends upon successful attenuation of the vibratory shaft torques and vertical forces which are generated in the rotor system. Thus these two aspects of rotor response dynamics have a large impact upon the simplicity, weight, and cost of a good isolation system. The technology is available for an effective effort to suppress these two aspects of rotor-hub loads and to reap the resulting benefits as isolator-system simplicity.

5.3 Configuration for High Research Payoff

Identification of technologies and areas of research which have high payoff potential must be judgmental and must be supported by an up-to-date review of fact and theory. Goals must be kept clearly defined and the physical implications for the cost-effectiveness of the vehicle design must be kept in view.

In the case of helicopter vibration control, the direction of effort must be kept in focus by maintaining a definition of the most attractive system-design approach to the problem. The high payoff potential will tend to be present in the simplest, lightest system design that will provide excellent results when all design interactions have been included in the judgmental process.

The high-payoff research effort may thus be identified as that needed to make a success of the simplest, lightest, fully effective system. It will advance the knowledge of the physics involved and it will include study of the design interactions to assure that the final approach is cost-effective as well as feasible. In light of the facts and theory reviewed during the present study, the system configuration which should be central to the continuing research is readily visualized.

The rotor system should provide for the use of shaft-bending loads to effect control and trim. The reason for this is that safe flight in the vicinity of zero g requires shaft moment as the mode of control. Thus the rotor could be either an offset-hinged type or hingeless. Furthermore, the successful isolation of teetering rotors without shaft moment control has been demonstrated and applied in production helicopters.

Thus the central research configuration should use an isolation system which is statically stiff but dynamically soft to pitch and roll moments. To isolate the relatively irreducible in-plane vibratory forces, the isolator system must also be dynamically soft to in-plane hub loads.

Details of the isolation system may vary with the number of blades and with the form of blade articulation, but the isolation arrangement will feature a focalized mounting of the transmission which uncouples the fuselage from vibratory shaft-bending moments and from in-plane hub vibratory forces. Transmission motion about the focal point will be restrained by two statically stiff but dynamically soft isolator devices. These can be either dynamic anti-resonant isolators, references 16 and 17, or they can be static trim-actuation devices in tandem with soft springs, references 18 and 19.

Completely passive isolation of vertical vibratory forces and of vibratory shaft torque should be provided and made as soft as possible within the practical mechanical limits of static deflections. The final values of transmitted vertical and torquewise vibration must be minimized by other design features which attenuate these aspects of the rotor response to airloads. Included among the candidate design features are blade-response dynamics, including aeroelastically adaptive features, elimination of aerodynamic interference, and the use of higher-harmonic-pitch control.

As a last resort, one or more absorbers may be added to clean up residual conditions, provided the overall result is the simplest, most cost-effective system design that can be attained.

6.0 RESEARCH TASKS TO FILL CURRENT TECHNOLOGY GAPS

The goal of a helicopter vibration-alleviation research program will ultimately be reached by evolving and demonstrating one or more excellent overall design approaches to the problem. Along the way, the current unknowns and the current gaps in the technology of design support must be probed and dealt with.

In arriving at the aforementioned description of a high-payoff research configuration, the current technology gaps have been evaluated. Prospective means of filling these gaps have also been searched and reconsidered. The judgmental process which has identified the suggested high-payoff configuration also placed the technological research needs in focus. The most urgent needs turn out to be in basic technology, rather than in applied research and demonstration. Relative importance of the known gaps in technology, both as immediate obstacles and for their longer-range significance, is clear enough to permit prioritizing attention to them.

The research tasks recommended to fill such gaps are discussed below in order of priority.

6.1 Task 1: Determine the Vibratory Airloads Which Force the System

The need. – The character of the vibratory airloads encountered by the blade and the way these airloads vary with operating conditions must be better established. This information is needed for input to dynamic analyses of rotor/isolator-system responses. It is also essential to the design of simpler, more effective isolation systems. Each of the forcing airloads must be determined in terms of its harmonic-content phase and spanwise distribution.

To facilitate interpretation and use of the information, those vibratory airloads which arise from the forward motion of an isolated rotor should be separated from those due to interference with other parts of the helicopter.

Research objective. – Explore the character of blade vibratory airloadings which must be dealt with in a vibration-alleviation system and convert the acquired information to a form which will support dynamic design of such systems.

Recommended method. – The blade airload components which force the vibration problem should be determined and mapped by examining data from suitable wind-tunnel and full-scale testing. This method might be followed by analytical efforts based upon calculation of wake geometry, but it is considered unlikely that the necessary knowledge can be generated in that manner within the near future. Results must cover the entire flight envelope, which would be a tall order for an aeroanalytical approach. If instead the necessary information is extracted from test data, the effects of all the flow complexities will be manifest in the needed airloads descriptions.

Two methods of reducing test data can be followed. First, where dynamic-pressure measurements have been made or are conducted in the future, the data should be harmonically analyzed and reduced to form which can be input to rotor dynamic-response analytical programs. An informative start on this approach has been made under past flight-test programs

such as that reported in reference 21. Secondly, the response dynamics of the rotor can be treated as a known so that strain-gage data from the tests can be used to solve for the harmonic content of the airloads. Factors favoring the second approach include a large volume of available data from prior tests, the greater reliability and simplicity of strain-gage techniques, and their applicability to any type of rotor blade.

It is considered likely that the more advanced rotor-loads analytical programs now available can model the blade with sufficient accuracy. Therefore, the effort to solve for these airloads which are implied by measured bending data can be relatively straightforward. Methods for this purpose have been successfully applied in the scaling of wind-tunnel loads (ref. 22).

The analysis involved in deducing the airloads should be simplified by testing a model which is effectively uncoupled from the test stand for its response dynamics. This means that the essential airloads test measurements should be made with a model such as that previously described under "High Payoff Configuration". Such a rotor will feel zero test-stand impedance in those modes which are uncoupled and infinite impedance in those modes which are restrained by absorbers. Thus the test-stand impedance (or the fuselage impedance if in a flight test) can be excluded from the airloads data extraction computations. Variable isolation geometry should be provided in the model so that it can be adjusted for fully effective isolation under each condition at which airloads data is sought. This test approach can also serve to demonstrate the degree of suitability of a simplified isolator system when subjected to the entire flight envelope.

6.2 Task 2: Establish Methods for Quantifying Effects of Blade Aeroelasticity

The need. – The effects of blade aeroelastic deflections upon vibratory airloadings must be accounted for both in computer analytical programs and in the experimental evaluation and development of rotor/isolator systems.

Research objective. – Explore the effects of blade aeroelasticity upon the vibratory loads which reach the rotor shaft and develop analytical methods which account adequately for their influence upon system behavior.

Recommended methods. – It is obvious that the effects of blade aeroelasticity must be accounted for in any analytical program which is used to extract airload components from test data as proposed just above. The current work of reference 7, involving the wind-tunnel and analytical development of torsionally activated blades, is successfully employing the Boeing Vertol Company's computer program C60 which couples blade torsion to flap bending. While the purpose of the reference 7 work is flap-bending suppression and the opening of flyable speed and thrust limits rather than vibration attenuation, the analytical requirements for the blade dynamic-response aspects are the same.

Indications from the reference 7 work are that the C60 program is quite successful on the essentials of blade aeroelastic response, and could be much improved in its overall loads predictions if its airflow modeling were improved. This improvement to programs like C60 will be one goal of the airload data acquisition discussed in Task 1.

In substance, the research required to fill this second technological gap is the expansion of the work of reference 7, with added emphasis given to the prediction and use of blade aeroelastic behavior which will reduce the vibratory loads reaching the rotor shaft. Included should be exploratory testing of model and full-scale rotors to study the changes of aeroelastic effects which are favorable to the vibration-alleviation systems and to determine their interactions with other essential aspects of rotor behavior.

6.3 Task 3: Validate Rotor-System-Response Dynamics Programs

The need. – Each candidate system design will consist of a rotor system combined with an arrangement of isolation and/or absorption features. Blade-response dynamics will couple with other system elements so that computer programs which are limited to a single isolated blade are inadequate.

Research objective. – Develop and validate analytical programs which can model the blade dynamic system as coupled to the fuselage. Vibratory hub loads treated should include thrust, horizontal forces, shaft torque, and shaft bending. Programs should use downwash models which can be varied to conform to the airloading patterns found under Task 1.

Recommended methods. – Blade-response-dynamics analytical programs which are improved to achieve the purposes of Task 2 should be expanded or used as modules in suitable programs which can model the blade as significantly coupled to all other elements of the system. The success experienced in modeling the blade's dynamic response for a current aeroelastically adaptive rotor-development project, reference 7, suggests that with the necessary couplings added, the response aspects of the problem can be handled by programs like C60. It is therefore recommended that the necessary extensions of C60 or similar programs be developed.

As with the response of an uncoupled blade, it will be necessary to improve the airloading model. To get a valid computation of the loads that will pass through the rotor shaft and involve the isolator/absorber elements of the system, the higher-harmonic content of airloadings must be accurate. This should be approached by providing for the input of refined downwash patterns which are derived from the airloads data obtained under Task 1.

The complexity of the necessary programs can be reduced where it is recognized that uncoupling by the isolator/absorber system will prevail. As discussed under Task 1, simplifications based upon such uncoupling should be emphasized and used wherever feasible.

6.4 Task 4: Investigate the Design Features that Influence Vibration

The need. – A methodical study should be started and maintained to determine how the character and magnitude of vibratory shaft loads can be expected to change with changes of the essential helicopter design parameters. Included should be the effects of changing the number of blades, their taper, twist, and tip shape. Unsymmetrical rotor geometry should be further examined as in reference 14. Major design variables such as disc loading, advance ratio, and the depth of stall penetration should also be explored.

Research objective. – Expand and record an understanding of the ways in which the vibration-alleviation problem will be affected by parametric changes to the other aspects of helicopter design.

Recommended methods. – As the improved knowledge and capability sought in research Tasks 1 through 3 become available, a methodical study should be made to determine how the character and level of vibratory shaft loads can be expected to change when the basics of the helicopter design are changed for any purpose. Emphasis should be placed upon factors like reduced tipspeed and increased advance ratio, which are foreseeable features of the future civil helicopter.

These studies should be expanded gradually as it becomes possible to be sure the systems that are modeled have been optimized. The effects of adverse blade aeroelasticity and poor response dynamics must be designed out of the parametric study models.

6.5 Task 5: Refine and Develop Isolation Devices

The need. – Devices which provide statically stiff coupling between two system elements while uncoupling them for vibratory motions are clearly needed. They must be as efficient, simple, reliable, and light as technology can make them. This need is in addition to the need to devise simple isolation systems which use a minimum number of isolation devices.

Research objective. – Advance the design technology of presently conceived isolation devices and foster the conception and evaluation of new or improved approaches to providing statically stiff but dynamically soft coupling devices.

Recommended methods. – Current and future concepts for potentially useful isolation devices should be explored, refined, and compared to assure that all prospective solutions are evaluated. At present, design and development are advancing the technology of two such devices, the dynamic antiresonant vibration isolator, references 16 and 17, and the actively trimmed all-frequency isolators, references 18 and 19. Other, more complex devices or subsystems which serve the same purpose have been explored, references 20 and 23. Such research should continue, with emphasis placed upon comparative evaluation of all concepts and upon finding the simplest, fully effective overall system. All design interactions must be evaluated.

6.6 Task 6: Refine and Develop Absorption Devices

The need. – Devices which absorb vibratory forces as they are felt at a selected point in the system and thus enforce local fixity may be useful elements in the ultimate system, especially if they serve to permit great simplification of an associated isolation system. This despite the fact that the best absorber has a weight penalty inevitably proportional to the loads it must absorb.

Before absorbers can be confidently traded off against the costs of complexity and the design interactions involved in an all-isolation approach, it must be clear that the absorber design is mature and satisfactory.

Research objective. – Advance the design technology of presently conceived absorption devices and foster the conception and evaluation of new approaches with the objective of establishing a firm knowledge of the cost/benefit effects that can be achieved.

Recommended methods. – Current and future concepts for the improvement of dynamic vibration absorbers should be examined and the near-term development of such devices should be encouraged. Emphasis should be placed upon achieving efficiency and reliability. Included in the evaluations should be centrifugal pendulum absorbers in all forms for use in the rotating system, also the several forms of tuned absorbers for use in the nonrotating systems, reference 24.

6.7 Task 7: Investigate Higher-Harmonic Pitch Systems

The need. – Prospective simplification of an isolation system can be sought by selecting alternate methods of suppressing one of the vibratory loads at the rotor hub. Higher-harmonic pitch (HHP) is one such method. For example, higher-harmonic collective pitch applied below the swashplate can cancel vertical vibratory forces, relieving the isolator system of that aspect of the problem (ref. 12).

More complex applications of HHP could conceivably cancel two or more aspects of the loading which must be isolated, but the elements of a mature, reliable HHP system have yet to be fully visualized and traded off against other approaches. Greater knowledge of the capabilities, complexities, and side effects of HHP is therefore needed.

Higher-harmonic-pitch systems were not given high priority in this task rating because of an admitted leaning toward the inherent simplicity and reliability of the isolation and system-dynamic-refinement approach. Further HHP investigation should be conducted because it is possible that still unconceived devices and subsystems could turn out to offer favorable trade-offs in partial or total substitution for isolation systems.

Research objective. – Advance the conceptual design of HHP devices and subsystems and explore the side effects and design interactions which will be encountered, with the objective of establishing a firm knowledge of the cost/benefit effects that can be achieved.

Recommended methods. – Recent investigations of higher-harmonic blade-pitch control as a means of vibration alleviation should be extended. Candidate devices and subsystems should be studied for their interactive effects. Emphasis should be placed upon prospective simplification of an isolation system by using higher-harmonic pitch to handle a portion of the problem. Design investigation should be carried to a point enabling evaluation of the pitch control and associated sensors as alternatives to other elements in a fully effective vibration-alleviation system.

6.8 Task 8: Develop Techniques to Attain Excellent Rotor Symmetry

The need. – All blades in a rotor must be identical and carry identical shares of the steady rotor thrust if the maximum, clean cancellation of harmonic components of vibratory loads within the hub is to occur. If this state of symmetry is not attained, there will be vibratory loads that will pass through the shaft at all integer multiples of rotor rotational frequency. At best, the result will be a burden on the isolation system, which must then have an all-frequency capability.

This rudimentary view of the effects of rotor dissymmetry points up the importance of the balance and track aspects of the overall vibration-attenuation problem. It is essential that production blades be adjusted to identicalness and kept that way. The rotor must also be balanced or adjusted to dynamic symmetry in all its essential forms..

Research objectives. – Establish tolerances on all forms of blade mismatch and rotor dissymmetry which will eliminate that source of discernible vibration. Establish production and service techniques which will assure that all blades are adjusted to tolerance and that rotor-hub assemblies and control systems are also.

Recommended methods. – Current techniques in the dynamic balancing of rotors and aerodynamic matching of rotor blades should be reviewed for adequacy and should be improved. Methodical testing should quantify the sensitivity of the total vibration problem to blade mismatch in all its forms. Design features for more complete blade balancing and aerodynamic trimming should be tested to establish tolerances for their use in adjusting blades toward a state of match that will eliminate discernible vibration from that source. Features for the mechanical adjustment of rotor assemblies to suitably close tolerances on symmetry should also be tested and applied in both production and field techniques.

This task is in the realm of applied rather than basic technology development. It will require increasing emphasis as progress is made in correcting the vibration problems inherent to a symmetrical rotor. Learning to correct dissymmetries is analogous to wheel-balancing in highway vehicles, while the above basic-research tasks are analogous to improving suspension design.

While this task cannot be launched and completed in any short-term research program, its purposes must be given attention during all the other research tasks. It involves the continuing objective of learning and recording the best means of attaining excellent rotor symmetry.

6.9 Task 9: Achieve Optimum Fuselage Modal Natural Frequencies

The need. – Even if absolute success were attained in isolating the fuselage from vibratory loads within the rotor system, there would still be aerodynamic fuselage excitations at multiples of blade-passage frequency. Configuration layout can reduce, but cannot eliminate, this source of vibratory excitation. Thus excellence of vibration control will never be achieved without careful attention to fuselage modal natural-frequency design. Work toward that end

is among the oldest technology for helicopter vibration alleviation but, with new analytical techniques such as NASTRAN and with improving test techniques, the subject is becoming a matter of applied research and development rather than basic research.

In the course of this overall research program, care must be taken to be sure that good fuselage-response dynamics are present in the designs under study. Care must also be taken to account for the modal-frequency changes which result from partial to total uncoupling of the rotor and transmission through the action of isolation features.

Included in this aspect of the applied research will be the suitable detail use of composite materials to help tailor modal frequencies while meeting other physical demands of the fuselage design. This, too, tends to fall in the realm of advanced development rather than research.

Research objective. – Establish analytical and experimental techniques which will aid the attainment of optimum modal natural frequencies in helicopter fuselage structures. Apply emphasis to analytical methods which recognize the uncoupling effects of isolation systems and to test methods which will aid and confirm the achievement of optimum fuselage tuning.

Recommended methods. – Current techniques and analytical tools for the prediction, adjustment, and design achievement of optimum fuselage modal natural frequencies should be reviewed, evaluated, and improved. Opportunities to do so are present in the maturity development cycle of each new design.

In substance, this task should be a continuing one which observes and records the experience gained from each design/development project. It should also aid each project by creating a source of information on past successes and failures.

The knowledge accumulated under this task should be assembled in the form of validated computer programs and case histories of the design features found to provide success.

7.0 PROGRESSION FROM BASIC TO APPLIED RESEARCH

It is noteworthy that the higher-priority research tasks recommended are of a basic nature. Their identification reflects a need for a better understanding of the physical details of a very complex problem. The initial effort should get down to basics and build technological understanding which can be applied in design solutions.

Testing of physical models or full-scale systems must be conducted in a manner that will reveal the causes of progress. It must also enable the improvement and validation of computer analytical programs. Confirmation of progress will be seen in the improving behavior of systems – first in wind-tunnel models, then in full-scale applications of the new technology.

Improvement of wind-tunnel model systems and of system mathematical models is viewed as basic research. That phase should be pursued until high confidence is felt that the superior systems have been identified. Subsequent full-scale systems will move the research through the refinement and demonstration stages.

The transition from basic to applied research will tend to be complete when a full-scale configuration has become substantially firm. As the program enters the applied-research stage, it will no doubt expand to include demonstration on several types of helicopters having basically different rotor systems and designed for different operating requirements.

8.0 IMPACT OF TECHNOLOGY/DESIGN INTERACTIONS

8.1 Design and Technology Must be Blended

Interaction between basic technology and design will be absolutely essential to the attainment of the subject goals. As the technological understanding is expanded it must be applied in design studies, first to evolve experimental systems, then to evaluate the safety, weight, reliability, and cost effects that can be foreseen in mature, improved systems. Finally, the design trends flowing from the research must be continuously evaluated in search of indicators that redirection should be considered.

The present study has amounted to a situation review of the design state of the art and of the present trends of technological understanding. It has resulted in a proposed redirection which is expressed in the nine recommended research tasks.

8.2 Interactive Effects of Design Features

Each of the several conceptually different approaches to vibration alleviation which are available for pursuit has its effects upon design. Each involves design features which interact with the rest of the vehicle design, some with compounded benefits, some with new costs or functional penalties.

Table 8-1 presents the matrix of interactive design effects which were considered in arriving at the described high-payoff configuration and the recommended research program. Presuming that the judgments expressed in the matrix are correct and that the high-payoff configuration does emerge as superior, the effects upon helicopter cost, utility, and productivity can be envisioned as follows.

Production. – Two or more isolation devices must be added to the basic helicopter parts list. These devices will be new arrangements of state-of-the-art hardware. They will involve production technology comparable to that now involved with lead-lag dampers or pendulum absorbers.

Except for these isolation devices, the physical changes to design should occur at no extra production cost because they will merely involve rearrangement of present elements in the mounting of the transmission.

There will be no clear-cut parts elimination or production cost saving as compared to present helicopters which lack vibration treatment such as absorber systems. For a comparable level of vibration alleviation achieved, however, the production cost should be substantially lowered when isolation replaces absorber systems.

If the isolation devices turn out to be of a passive, all-frequency type, significant production costs may be eliminated because blade-match tolerances can be relaxed and tuning routines on both absorbers and dynamic isolators will be eliminated.

TABLE 8–1. OPTIONS IN TREATMENT OF AIRFRAME-VIBRATION TECHNOLOGY/DESIGN INTERACTIONS

Treatment \ Interaction	Cost/ Production	Empty Weight	Safety	Maintenance	Rotor Loads
I. Selected for High-Payoff Research Configuration					
Reduce Configuration Interferences	No change	No change	No change	No change	Lower
Aeroelastic Adaptivity in Blades	No change	No change	Increase	Lower	Lower
Tailor Rotor-System Dynamics	No change	Lower	Increase	Lower	Lower
Uncoupling of Transmission	No change	No change	Increase	Lower	No change
Tuning of Fuselage Modal Frequencies	No change	No change	Increase	Lower	No change
Improve Rotor Symmetry	No change	No change	Increase	Lower	No change
II. Excluded From Research Configuration					
Increase Number of Blades	Higher	No change	No change	Higher	No change
Absorbers in Rotating System	Higher	Higher	Lower	Higher	No change
Uncoupling in Rotor Shaft	Higher	Higher	Lower	Higher	No change
Absorbers in Fixed System	Higher	Higher	No change	Higher	No change

Empty weight. – A successful program should achieve the goals with an empty-weight reduction rather than an increaase. The basis of that judgment is that the weight now spent upon vibration-protective measures throughout fuselage-mounted systems will exceed the weight of isolation devices.

Weight saving is most likely to be achieved if absorbers are not used in the system. The second hazard to the saving of weight is the use of dynamic antiresonant isolators because they, too, involve parasitic mass. If the solution is accomplished with passive isolation and active trimming of static deflections in the isolators, the concomitant savings of empty weight should be achieved.

Safety. – There are no discernible, additional hazard or safety maintenance routines involved. Overall effects upon safety should be positive because the hazards associated with vibration-induced failures of all fuselage-mounted systems should be virtually eliminated.

Maintenance. – Substantial reduction of maintenance activities and related costs should accrue. Less-significant reductions of general vibration level than are sought here have been shown in field tests to have large favorable effects (ref. 1).

The maintenance of the isolation devices would be the only additional activity. If these devices turn out to be of a passive, all-frequency type, significant maintenance cost and reliability gains may accrue because blade track and balance tolerances can be relaxed and tuning routines on both absorbers and dynamic isolators will be eliminated.

Rotor loads. – There will be no significant effect upon rotor loads insofar as blade and hub structural requirements and prospective fatigue life are concerned. This whole effort deals in a different treatment of the presently small, higher-harmonic content of blade loads rather than in the structurally significant content of those loads.

By extending the defin' n of rotor loads to include vibratory torques in the drive train, significant benefits can be predicted. Minimizing vibratory torques which would reach the fuselage through the transmission case will also reduce the vibratory loads for gears, bearings, and high-speed shafting.

9.0 RECOMMENDED RESEARCH PROGRAM

To support the design of vibration-free helicopters an improved technology base must be established. This in turn requires that the present technological gaps be filled through a suitable research effort. Basic knowledge of the physics of the problem must be obtained and embodied in analytical methods useful to the designer. It must also be demonstrated that the methods developed are successful.

Viewed in this manner, it becomes apparent that the research objective is establishment of a capability to design for the needed results. The nine research tasks previously discussed are not economically amenable to treatment as individual projects. Instead they are need-to-know items which should be pursued through a combination of analytical and experimental efforts. It is recommended that this be done by conducting a program of experimental refinement of the high-payoff research configuration.

If permitted by available funds, the work should be conducted on both a hingeless configuration with three or more blades, and on an articulated configuration with offset flap hinges. If parallel investigation of both configurations cannot be funded, the initial effort should go to the hingeless configuration. The reason for this is that the probable relative gains are greater and the technical complexity of achievement is probably less for the hingeless system. In addition, the bulk of knowledge gained from the hingeless investigation would apply to later efforts with an articulated system.

Outlined below is a combined analytical, wind-tunnel, and flight-test program which would take the high-payoff configuration through experimental refinement and demonstration of a flight vehicle. While it is most apparently an improvement and demonstration program, the essential end product would be an upgraded technical position in each of the nine present gaps.

Unlike a typical development program where technical interest in the causes of failure is minimal, this program must be designed to emerge with the fullest possible grasp of the physics of the problem. It must explore off-optimum conditions with interest sufficient to confirm theory and validate analytical methods as they evolve. Demonstrated success must be accompanied by validated theory which permits design for repeated success.

9.1 Research Program Outline

Although wind-tunnel testing cannot simulate all the flight conditions which must be accommodated in an eventual design, its economy and its flexibility in the making of parametric changes make it an essential starting point. The family of investigations should be started with wind-tunnel models and phased into full-scale tests as concepts and knowledge become firm enough to be further explored under the constraints of flight testing. Analysis of rotor-response dynamics should be applied to all test data in a manner which extracts knowledge of the vibratory airloads encountered.

Figure 9-1 charts a research program which would fill the more basic and urgent technology gaps and demonstrate a successful configuration in five years. The program would continue as shown, to explore additional configurations and technological refinements between the fifth and tenth years. Because the first five-year effort is rather clearly defined and limited in scope, it is reasonably amenable to cost estimating. The cumulative expenditures charted in Figure 9-2 are about double what would be expected if the work were confined to merely making the subject configuration work. The difference lies in the cost of the effort to explore the physics thoroughly and come up with basic, documented technology for future use.

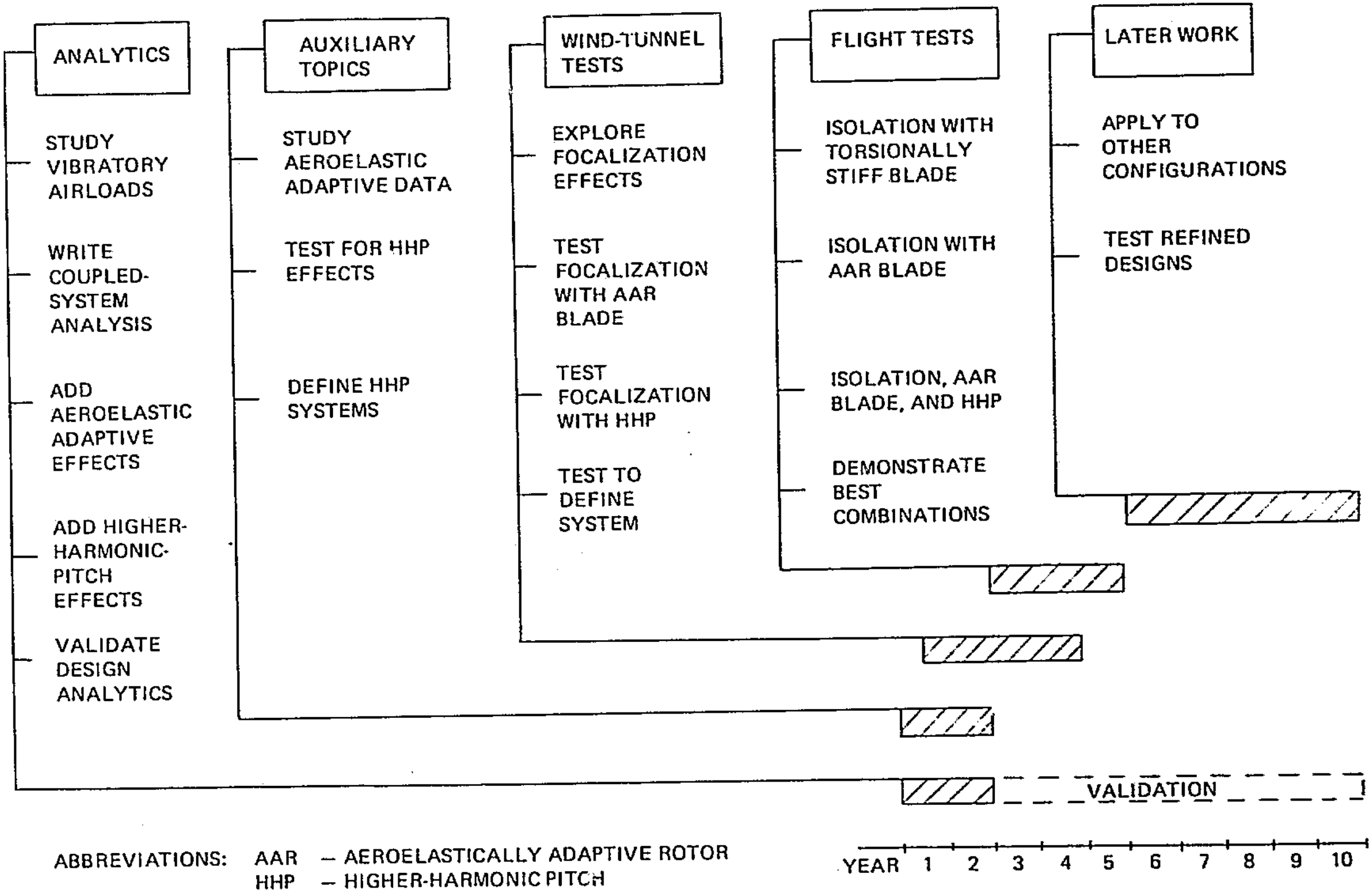

Figure 9–1. Recommended program for vibration-reduction research

COST BREAKDOWN, $ THOUSANDS	
ANALYTICAL DEVELOPMENT	$ 700
DATA STUDY AND REPORTS	1,000
WIND-TUNNEL MODELS AND TESTS	900
FLIGHT-TEST VEHICLE AND MODS	1,000
CHANGES DURING FLIGHT TESTS	500
THREE FLIGHT TESTS	1,200
AUXILIARY INVESTIGATIONS	1,000
	$6,300

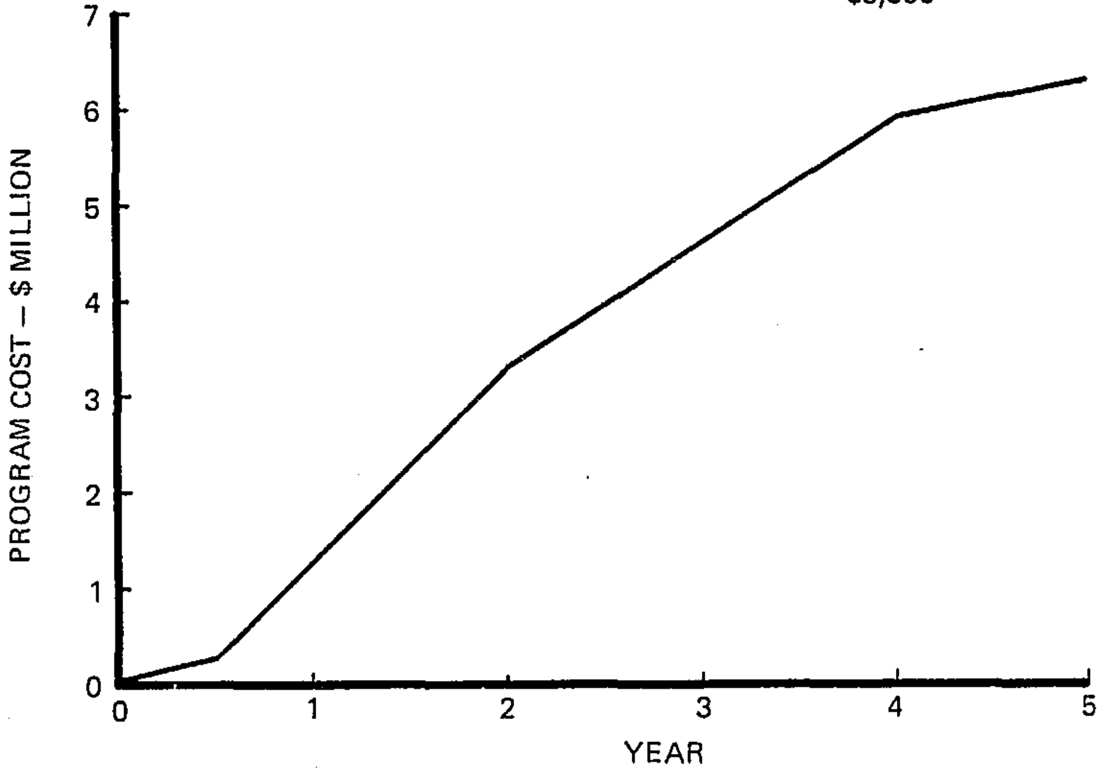

Figure 9–2. Cumulative expenditures for vibration-reduction research

10.0 CONCLUDING REMARKS

Results of a study of the state of the art in the treatment of helicopter vibration problems reveal several clear-cut voids in the basic technical knowledge now available. As shown in Table 10-1, the research tasks that would serve to close these technology gaps can be conducted in a sequence that recognizes both relative urgency and orderly procedure.

Trends in the progress made to date are related to acceptance or rejection by designers of the need to bring suitable advanced dynamics into play. Reluctance to do so has been attributed to lack of knowledge – to the assumption that the matter was too complex to handle except by cut-and-try methods.

The research program needed to correct this situation is necessarily broad, but not difficult to formulate, as has been done in this report. Its completion will put the designer in a position where he knows what can be accomplished and how he must proceed.

TABLE 10–1. SUMMARY OF RECOMMENDED RESEARCH IN ORDER OF PRIORITY

Task Title	Class	Current Status	Applicability: Size	Applicability: Configuration
Determine Vibratory Airloads	Basic	– No effective start as yet – Methodology available	All	All
Establish Blade Aeroelasticity Methodology	Basic	– Excellent start exists – Other projects are aids	All	All
Validate Rotor-System Mathematical Modeling	Basic	– Excellent start exists – Need is progression from blade to system modeling	All	Involves specialization
Investigate Design Features That Influence Vibration	Basic	– No effective start as yet – Methodology undeveloped	All	Variable
Refine and Develop Isolation Devices	Applied	– Projects under way on two diverse concepts	All	All
Refine and Develop Absorption Devices	Applied	– Numerous projects have reached production	All	All
Investigate Higher-Harmonic-Pitch Systems	Basic to Applied	– Tests have demonstrated the effect – Systems unvisualized	All	All
Develop Techniques to Attain Excellent Rotor symmetry	Applied	– Need has been hidden by high Nr vibration – Relatively unexplored	All	All
Achieve Optimum Fuselage Modal Frequencies	Applied	– Methodology exists – Needs vigilant attention	All	Involves specialization

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